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5aMUa3. Sound analysis and synthesis of Marquis Yi of Zeng's chime-bell set**Chih-Wei Wu*, Chih-Fang Huang and Yi-Wen Liu**

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In this paper, the analysis and synthesis results from a complete set of Chinese chime-bells (also known as Chinese two tone bells) are presented. Consisting of 65 bells with different sizes and tones, Marquis Yi of Zeng's set is an ancient musical instrument with fascinating acoustical features but scarcely appears in current music performances for being huge and inaccessible. To preserve this cultural legacy in digital form, sounds of a complete set of replicated Marquis Yi of Zeng's chime-bells were recorded and analyzed, and the pitch discrimination of fundamental frequencies between this replica and the original set has been evaluated. Sound synthesis models of chime-bells were constructed using multiple inharmonic digital waveguides, creating chime-bell like sounds. Quality of synthetic sounds was evaluated using both objective and subjective measures. Objectively, the similarity between synthetic and recorded sounds was compared in both the spectral and the temporal domains. The subjective measure was achieved through listening tests. Results show that sounds from different bells on the rack could be successfully generated from the proposed models, leading toward the realization of virtual chime-bell set in the future.

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1. INTRODUCTION

Chinese chime-bell, one of the greatest inventions in Chinese history, is an ancient musical instrument that is well tuned and carefully crafted. Once the symbol of authority and rank, Chinese chime-bell was a luxurious installation in palace or ceremony, entertaining the nobles with the elegant sounds and pleasing appearance. Dated back to around fifth century B.C., Chinese chime-bells show not only the craftsmanship of Chinese civilization, but also the music knowledge of the past. Therefore, it has been an exciting topic for scientists of different fields to explore.

The acoustical features of Chinese chime-bells (Shen, 1987) are different from the western bells (Rossing, 1984) in many aspects. The most obvious difference would be the appearance. As shown in figure 1(a), the chime-bell is oblate in shape, while most of the western bells are round and symmetric. Also, the sounds from the western bells tend to warble and last, whereas the sounds from Chinese chime-bells fade away quickly. Most of all, the chime-bell is capable of producing two tones from one single bell according to the location of the strike. For instance, when the bell is struck at the location of Sui in figure 1(b), a lower pitched tone is excited; when the bell is struck at Gu, a higher pitched tone is excited instead. In general, these tones have an interval of major or minor third.

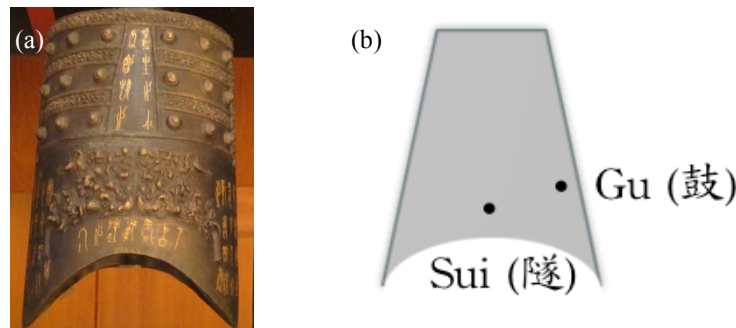


FIGURE 1. (a) A Chinese chime-bell. (b) Two strike points of the bell.

To account for this phenomenon, the vibrational modes of a modern copy of Chinese chime-bell has been studied (Rossing et al., 1988). It was concluded that vibrational modes of the Chinese chime-bell tend to exist in pairs and can be labeled as $(m,n)_a$ and $(m,n)_b$, where m and n represent the number of the nodal meridians and nodal circles respectively. This is because of the asymmetric nature of the chime-bells, and these two sub-modes have opposite locations of their nodes and anti-nodes. The other features, such as the short decay, the effect of temperature, and the effect of Mei (the ornaments on the bell) have been well discussed in previous studies too (Chen et al., 2009; Jing, 2003; Yan et al., 2004).

There were many sets of bells discovered in Mainland China, and each set had its combination of bells and different tonal scales. Among those, the most famous set would be the one discovered in the tomb of Marquis Yi of Zeng in 1978 in province of Hubei (Chinese Academy of Social Sciences, 1989). The whole set consisted of 65 bells with weights range from 4.2 to 203.6 kilogram, manifesting the diversity of the bells. The bells are made of bronze, and the surfaces are decorated with inscriptions and embossments. Despite of having these fascinating features, this ancient musical instrument is currently underused for being too large in size and too expensive to build. This makes virtual instrument a very appealing solution to the problem.

Most studies about synthesis models of musical instruments mainly focused on Western musical instruments such as guitar (Karjalainen et al., 1993), piano (Smith and Duyne, 1995), and woodwind instruments (Scavone, 1995), only a relatively few attentions were put on Eastern musical instruments (Chen and Huang, 2011; Penttinen et al., 2006). Besides, previous investigations on the acoustical properties of the chime-bells mainly provide information of one single chime-bell. The study of a complete set of bells is scarce (Pan, 2009). Hence, the goal of this paper is to study the acoustical properties of a complete set of replicated chime-bells of Marquis Yi of Zeng, and construct an efficient sound synthesis model accordingly.

2. ACOUSTIC SIGNAL ANALYSIS

2.1. Chime-Bells Sampling

To better understand the acoustical properties of a chime-bell set, qualitative samples from the bells are required. In this study, a replicated set of Marquis Yi's Chime-bells, one of the collections of National Center for Traditional Arts in Taiwan, have been sampled and analyzed as the reference sounds. The sample recording was taken place in Taipei Zhongshan Hall. Since the space is designed specifically for musical performances, the environmental noises have been reduced to the minimum level. The room temperature during the recording process was about 25 degree Celsius.

The configuration and the naming rule of the Chime-bells are shown in figure. 2. There are three racks of bells, each rack has three levels, and the bells are placed on each level in the order of their sizes. A total of 65 bells are included in this set, and 64 of them are two-tone bells. Both the Sui and Gu tones were sampled for each bell. A well-trained musician participated the recording session, and every note was performed with similar loudness. Two condenser microphones were used in the process, one is for the direct sound from the instrument, and the other is for the ambient sound of the room. These sound tracks were later mixed and stored in the computer. The samples were all recorded and save in the format of 88.2 kHz sampling rate and 24-bit resolution.

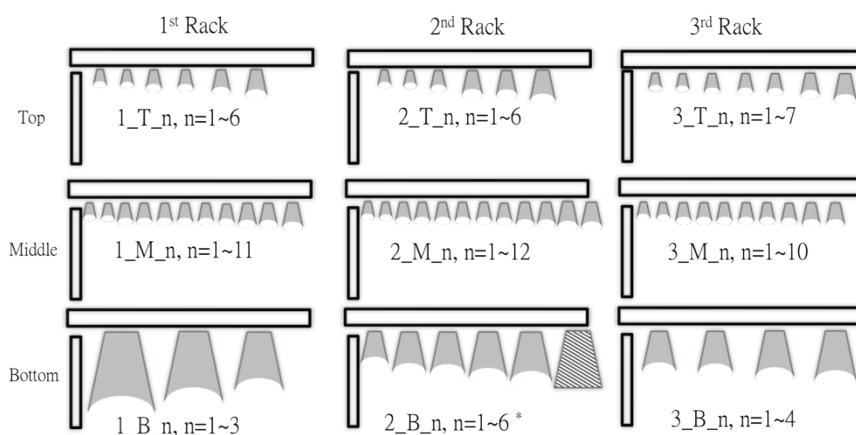


FIGURE 2. Configuration of the bell set.

2.2. Sound Analysis

2.2.1. Pitch Discrimination

According to Chinese Academy of Social Sciences (1989), the fundamental frequencies of all bells were measured by three different groups after the discovery of the tomb of Marquis Yi of Zeng. These data could be used to investigate the differences between the original set and the replicated set. The fundamental frequencies of the recorded samples in this paper have been measured through Fast Fourier Transform (FFT) with the hamming window and a window length of 4096 samples. The pitch discrimination of fundamental frequencies between these two set can be thus calculated.

Pitch discrimination is defined as the ability to hear the small difference in pitch (Seashore, 1938). The average threshold of adults is about 3Hz at the pitch of 435Hz, which is about 1/17 of a whole tone. However, for sensitive people or well-trained musicians, the threshold could be less than 1/100 of a tone. The threshold of pitch discrimination could be converted to a percentage error of 0.72%. To find out if there is any significant difference in pitch for every bell, the absolute percentage error (APE) between the original set and the replica could be calculated in (1), where V_a is the actual value and V_m is the measured value:

$$APE = 100\% \times |(V_a - V_m) / V_a| \quad (1)$$

The statistic result is shown in Table 1. Since there are 64 two-tone bells, a total number of 128 tones have been evaluated. Result shows that about 74.2% of tones are under the threshold of pitch discrimination. Besides, the first rack has the highest percentage of tones under the threshold. As a result, the recorded samples are acceptable as being the reference for synthetic sounds, and the first rack is the main subject of the study at current stage for its higher quality.

TABLE 1. Statistic results of APE evaluation

Racks	Under Thresh.	Exceed Thresh.	Total	Percentage
1st	31	9	40	77.5%
2nd	33	13	46	71.7%
3rd	31	11	42	73.8%
Total	95	33	128	74.2%

2.2.2. Spectral Analysis

To gather more information from the recorded samples, both the time and frequency-domain features of the signals have been examined. From the time domain signal, it shows that the duration of the bells is roughly proportional to its size, and the T_{60} ranges from 3.7 to 27.2 second. From the spectral analysis, it can be found that the bells with different fundamental frequency have different harmonic structures. For bells with fundamental frequency higher than 1000 Hz, the first and second harmonics are less stretched. However, for bells with fundamental frequency lower than 1000 Hz, the higher harmonics tend to be stretched away.

Even though the mode $(m,n)_a$ and $(m,n)_b$ have opposite positions of their nodes and antinodes, they still coexist in both the Sui tone and the Gu tone. Results can be found in figure 3 that the frequency components in both sounds are very similar except for their magnitudes. This result suggests that the sounds of the Chime-bells could be the weighted combination of two different groups of modes.

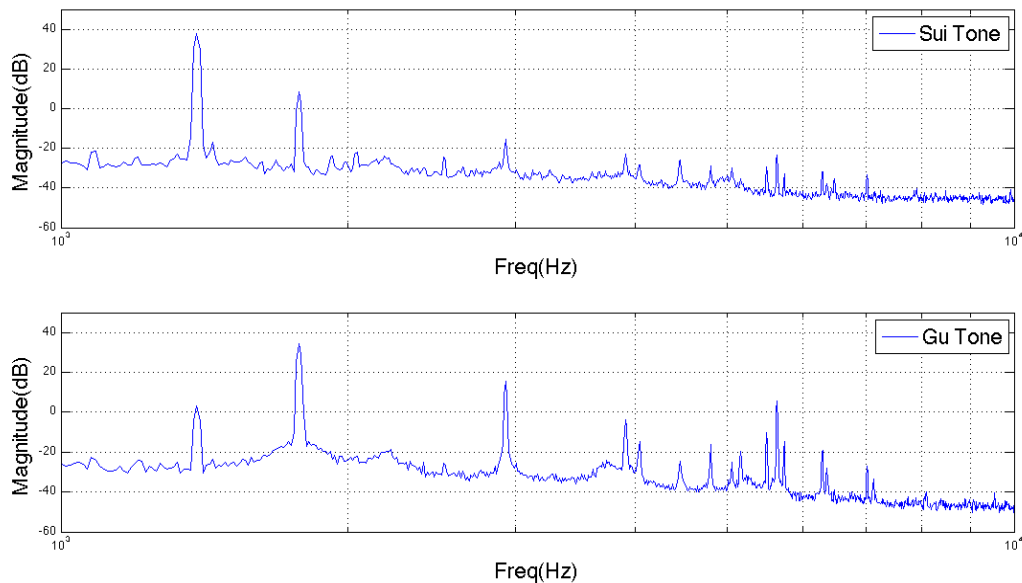


FIGURE 3. Spectrum of Sui and Gu tone of 1_T_2

3. SOUND SYNTHESIS OF THE CHIME-BELLS

To simulate the inharmonic sounds from the bells, an efficient model through the use of inharmonic digital waveguides has been proposed (Karjalainen, 2002; Karjalainen et al., 2003). The original digital waveguides (Smith, 1992) are suitable for synthesizing harmonic sounds with exponential decays. By adding a second order all-pass filter into the feedback delay loop, the waveguide model was able to generate sounds with stronger inharmonic partials. For psychoacoustic reasons, three matched frequencies would make a pretty convincing sound of bell. Therefore, the second-order all-pass filter is chosen on the account of the balance between authenticity and efficiency. The pole of the all-pass filter can be placed to attract nearby partials, causing them to shift away from their original positions and leading to inharmonicity. This approach provides a simple and efficient solution to the construction of bell model.

In Fig. 4, the block diagram of the sound synthesis model of the Chime-bells has been shown. The essential parts of the model include an input dynamic control and a bell model. The dynamic control consists of the excitation table and a low-pass filter (LP), which is to simulate the non-linear behavior of the strike (Smith and Duyne, 1995). It has been achieved by changing the cut-off frequency of the low-pass filter according to the initial collision velocity V_c . The excitation signals are obtained through inverse filtering.

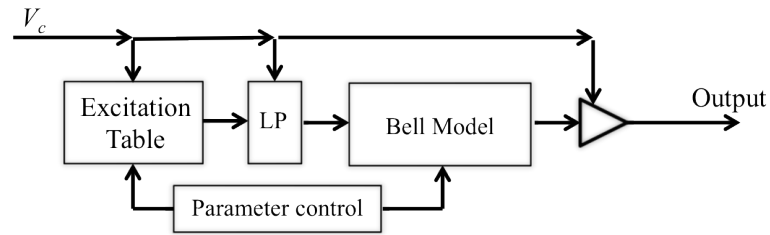


FIGURE 4. Block diagram of the Chime-bell synthesizer

The bell model is constructed based on the inharmonic digital waveguides. The loop filters of an inharmonic digital waveguide includes a fractional delay filter $H_f(z)$, a loss filter $H_l(z)$, and an inharmonic all-pass filter $H_{ap}(z)$. The transfer function of a single inharmonic digital waveguide can be expressed as equation (2) where L is the length of the delay loop:

$$H_i(z) = 1 / (1 - H_f(z) H_l(z) H_{ap}(z) z^{-L}) \quad (2)$$

Two bell models are constructed for different bells of the first rack. The model 1 in figure 5 (a) is to model bells with higher fundamental frequency by two inharmonic digital waveguides, which can be used to produce the selected partials of $(m,n)_a$ and $(m,n)_b$ respectively. The model 2 in figure 5 (b) is for bells with lower fundamental frequency. More waveguides are needed to account for the strong spectral stretch, and a structure similar to the banded digital waveguides (Essl et al., 2004) is applied here. To imitate the real sounds, the parameters and coefficients for the filters can be set based on the evaluation of the recorded samples.

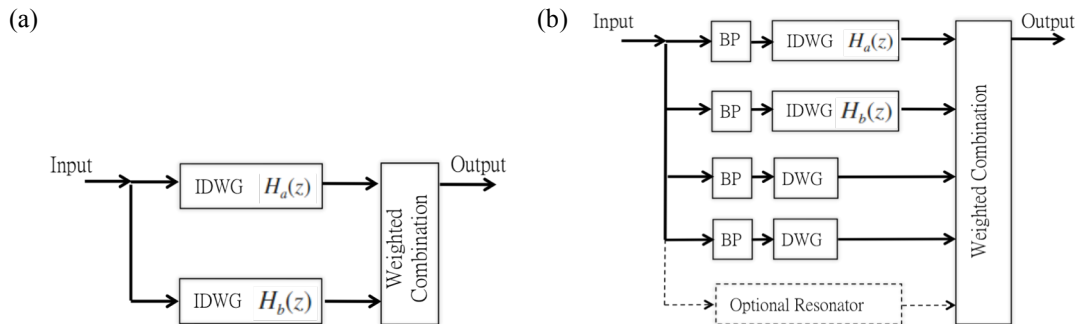


FIGURE 5. Block diagram of the bell models (a) model 1 (b) model 2

4. SYNTHETIC RESULTS

To cover the scale range of the first rack, five bells from different levels of the rack were chosen and synthesized. The sounds of 1_T_1 and 1_M_1 are synthesized by model 1, and the sounds of 1_T_5, 1_M_11 and 1_B_2 are synthesized by model 2. The waveforms of the synthetic and recorded sounds are basically matched, since the exponential decay of the bell sounds are not difficult to control. The spectra of the tones from both models are shown and compared in figure 6. It can be seen that there are fairly good matches for the lower frequency partials. However, mismatches can be found in the higher frequency partials. Some of the unwanted peaks in higher frequencies are relatively low in magnitude, yet still audible to the sensitive ears. These defects in the synthetic sounds might be due to the imprecise control over frequency components through inharmonic digital waveguides.

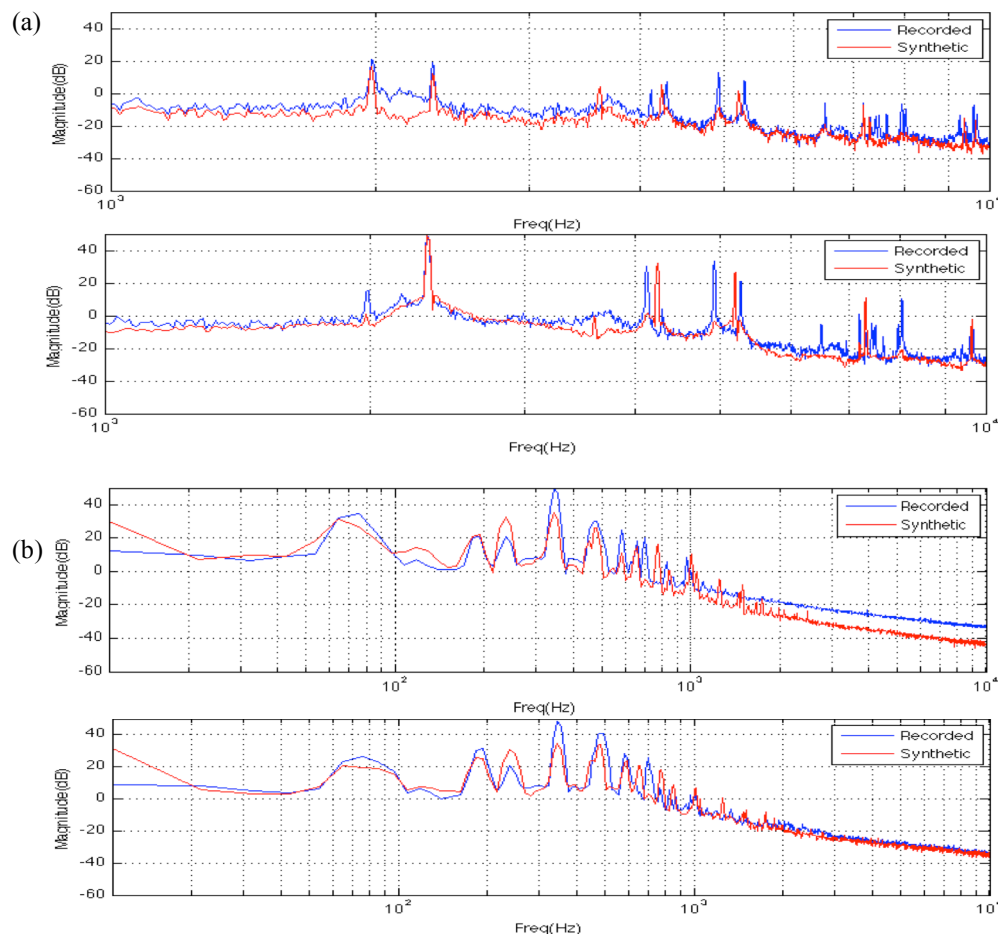


FIGURE 6. Spectra of (a) 1_T_1 Sui (Top) and Gu (Bottom) tones (b) 1_B_2 Sui (Top) and Gu (Bottom) tones

TABLE 2. Statistic Results of the listening test (N=20)

	Similarity		Acceptability	
	Mean	Std. Deviation	Mean	Std. Deviation
Model 1	3.50	.78	3.92	.76
Model 2	3.72	.83	3.86	.88
All	3.63	.80	3.89	.83

To measure the quality of the synthetic sounds subjectively, the listening tests have been conducted. Both the similarity and the acceptability of the synthetic sounds have been examined. 20 subjects are randomly chosen from the population of 59 students majoring in music technology. Result shows that 70% of the subjects have played

musical instrument for more than five years. This indicates that most subjects have received musical trainings and could be more sensitive to sounds. The Cronbach's α from the test results is 0.881, indicating good reliability of the tests. Every tone has been graded by Likert 5-point scale, and the statistic results have been shown in Table 2.

5. CONCLUSIONS

In this paper, the computational sound synthesis models for the Chinese chime-bells are presented. The sound synthesis models are constructed to cover the scale range of the first rack of the complete set of bells, and they are capable of producing chime-bell like sounds efficiently. By adjusting the parameters, the model will enable users to generate the real or surreal chime-bell sounds through this implementation.

As the first step toward a better understanding of a complete set of chime-bells, this study mainly focused on the first rack of the set at current stage. In the future, the entire set of the bells will be studied in order to establish a more general model for Chinese chime-bells. Also, more efforts will be put on the real time implementation of this virtual instrument. Hopefully, this research may serve as an alternative way to preserve the cultural legacies, and contribute to the diversity in this field of study.

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